ERAL
EARCH PROGRAM
ROVEMENT PROJECT
D UCIBILITY PROGRAM
ILDING THE NATIONAL
VT PROJECT SHIPBUILDING
UTOKON '71 RESEARCH
) COATINGS PROGRAM
ROVEMENT PROJECT
i TO SHIPBUILDING
DLING PROGRAM
DING

Investigation of Welding Processes for Low Temperature Applications

Project Report by Bethlehem Steel Corporation in cooperation with U. S. Maritime Administration

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **1971**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Investigation of Welding Processes for Low Temperature Applications**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Surface Warfare Center CD Code 2230 - Design Integration Tools Bldg 192 Room 128 9500 MacArthur Blvd Bethesda, MD 20817-5700**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**49**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

ERAL

EARCH PROGRAM

ROVEMENT PROJECT

D UCIBILITY PROGRAM

lLDING THE NATIONAL

VT PROJECT SHIPBUILDING

UTOKON '71 RESEARCH

COATINGS PROGRAM

ROVEMENT PROJECT

) TO SHIPBUILDING

DLING PROGRAM

DING

Investigation of Welding Processes for Low Temperature Applications

Project Report by Bethlehem Steel Corporation in cooperation with U. S. Maritime Administration

FOREWORD

This investigation presents the results of one of the research and development programs that was initiated by the members of the Ship mo- duction Committee of the Society of Naval Architects and Marine Engineers and financed largely by government funds through a cost sharing contract between the U. s. Maritime Administration, Bethlehem Steel Corporation and the American Bureau of Shipping. Mr. W. C. Brayton, Bethlehem Steel Corporation was the Program Manager. The program objective emphasizes productivity; the work was carried out to assess mechanized electrogas and electroslag welding processes for hull construction.

The program was carried out by the American Bureau of Shipping under the general direction of Mr. K. D. Morland and Mr. E. D. Swenson. Mr. B. L. Alia, was the Project Manager and Mr. I. L. Stern and Mr. C. Null served as Project Engineers. The service provided by members of the American Bureau of Shipping Metallurgy Laboratory under the technical laboratory supervision of Mr. C. R. Herbst is gratefully acknowledged.

In addition, the services of Bethlehem Steel Corporation, Sparrows Point Shipyard and Avondale Shipyard’s, Inc. in preparing the test weldments and the U. S. Naval Ordnance Station, Manufacturing Technology Department, Louisville, Kentucky in conducting the explosion bulge tests are acknowledged.

Finally, the assistance provided by Airco Welding Products Division of Air Reduction Company, Inc., Linde Division of Union Carbide Corporation and The Lincoln Electric Company in the preparation of exploratory weldments is appreciated.

INVESTIGATION OF WELDING PROCESSES

FOR LOW TEMPERATURE

APPLICATIONS

JANUARY 1979

EXECUTIVE SUMMARY

Background

Subsequent to the investigation entitled "Toughness Evaluation of Electrogas and Electroslag Weldment" completed in March 1975 by ABS under the welding research project 5P 1-3, sponsored by MARAD and ABS, several areas of work were indicated as desirable supplementary follow-on projects to develop technology to extend use of the higher heat input welding processes to shipbuilding for low temperature applications. This project deals with an investigation to determine the lower limits of temperature for satisfactory explosion bulge performance for Manual Metal Arc (MMA) and Submerged Arc (SAW) weldments in AMS Grades CS and EH36 materials.

Objective

The primary objective of this project is to evaluate and determine the lower temperature limits of satisfactory explosion bulge performance of the Manual Metal Arc (MMA) and Submerged Arc (SAW) weldments of Grade CS and EH36 material with a view toward determining their usefulness for low temperature service applications.

Achievement

The explosion bulge results indicate that MMA and SAW weldments can be expected to perform satisfactorily at -20F in ABS Grade CS and at -40F in ABS Grade EH36. In view of the above, these weldments are useful for the low temperature hull structure found in LFG and LNG liquified gas carriers. The applicable sections in the report "Toughness Evaluation of Electrogas and Electroslag Weldment" were revised to include the additional data and analysis for a further toughness estimate.

Background

As investigation entitled "Toughness Evaluation of Electrogas and Electroslag Weldsnent"[1] was completed in March 1975 by ABS under the welding research project SP 1-3, sponsored by MARAD and ABS. In this investigation the properties of welds in ordinary and higher strength hull structural steels made with electrogas (EG) and electroslag (ES) high heat input mechanized welding processes were compared with those from the manual metal arc (MMA) and submerged arc welding (SAW) processes with a view toward extending the applicability of the high input processes in shipbuilding. Comparisons were made with respect to toughness as evaluated by explosion bulge, Charpy V-notch (CVN), dynamic tear (DT), and drop weight tests (DWT). The investigation,which was exploratory in nature, provided several general conclusions relative to the applicability of the high heat input (EG and ES) welding processes to the ordinary and higher strength hull steels. (See Ref. 1- Conclusions). In addition, it indicated several areas of work which were logical follow-on projects to help develop the technology to extend use of the higher heat input welding processes to shipbuilding for low temperature applications. This report covers an investigation to determine the lower limits of temperature for satisfactory explosion bulge performance for MMA and SAW (triple arc) weldments in ABS Grades CS and EH36 materials.

Objective and Approach

In the initial investigation satisfactory performance was demonstrated in the large scale explosion bulge tests of the MMA and SAW Grade CS and EH36 weldments tested at 20F and OF respectively. It would be beneficial to determine the lower limits for satisfactory performance of these weldments in view of the wide utilization of these materials and welding processes in LNG ship hull lower temperature applications. At present, weld heat affected zone (HAZ) Charpy tests are required for these applications. In order to pass the HAZ requirements some shipyards have imposed heat input limitations for MMA and SAW processes resulting in a decrease in weld efficiency.

A number of explosion bulge specimens and pieces of weldments remained from the previous investigation.(1) This project involved utilizing the remaining Grades (CS and EH36 welded explosion bulge specimens to provide basic information on the toughness properties of-these weldments in the O to -50F temperature range. This temperature range is of primary interest for some LNG ship inner hull applications. Small scale toughness (CVN and DT tests were carried out and evaluated,and specific explosion bulge test temperatures were selected on the basis of these tests. Explosion bulge performance at the selected temperatures is evaluated and conclusions are given concerning the lower temperature limits of satisfactory performance of the MMA and SAW weldments of Grade CS and EH36 material. Applicable sections of Reference (1) were revised to include the data and analysis for this project and are reported herein.

Material Selection

ABS Grades CS and EH36 have been selected for this study since existing weldments prepared by MM and SAW with extensive base metal and weldment test data were readily available from previous work. (Reference 1). ABS Grades CS and EH36 or variation of these grades have been selected,and employed in the inner hull of LNG ship structures built in the U.S. and abroad. The toughness levels normally expected for these steels is 20 ft-lb at -40F and 25 ft-lb at -40F for Grades CS and EH36 steels respectively for longitudinal CVN tests, although it is quite common to find that longitudinal CVN properties of these base materials will satisfy a 20 ft-lb requirement at lower temperature say -50F and even -60F.

ABS requirement for low temperature steels is 20 ft-lb transverse at 10F below service temperature. By employing selected steel making practices including cross rolling a 20 ft-lb requirement in the transverse direction may be satisfied at the above mentioned -50F and -60F temperatures. However, the degree with which a 20 ft-lb transverse CVN requirement is satisfied is sometimes marginal due to variation in chemical composition, heat treatment, and rolling practice, including the amount of cross rolling.

Shipyards conducting weld- procedure tests, which included very detailed CVN tests in the HAZ, found in most instances-that even though the base plate material satisfied a 20 ft-lb CVN transverse requirement, the HAz results were marginal and sometimes failed to satisfy the same 20 ft-lb criterion. Shipyards have become acutely aware that-selected welding procedures need to be employed in order to satisfy the HAZ requirements. As a result modifications of the basic Grade CS and EH36 have been furnished which exhibited consistently better toughness in the base material in order to provide some margin for degradation during welding.

The use of Grades CS and EH36 in this program is intended to establish minimum temperatures at which adequate performance is found by both large and small scale toughness tests for weldments prepared with the weld axis perpendicular to the primary rolling direction.

It is reasonable to assume that the same minimum temperatures could be verified for weldments prepared with the weld axis longitudinal to the primary rolling direction provided base material with transverse properties comparable to the base material longitudinal properties utilized in this study, are employed.

MMA and SAW

MMA has been widely used for vertical position butt welds in special notch tough material such as ABS Grades CS, E and EH fitted in way of the sheer and bilge strakes of larger ships. SAW with single or multiple arcs has been used to make flat position erection butts in the decks of large ships. In Ships such as general cargo, container or ore carriers the deck stringer plates may be of special notch tough material such as ABS Grades CS, E or EH and have been welded by SAW when making erection butt welds in the deck. WhenMMA for butt welding of sheer and bilge strakes and SAw for butt welding of the deck stringer plates has been used, there has been no evidence of unsatisfactory performance or brittle fractures in way of these welds. In these applications the MMA process represents a low heat input process, approximately 50,000 joules/in. and the SAW a higher heat input process, approximately 75,000 to 100,000 joules/in. In this investigation a tandem, triple arc SAW process with a heat input of approximately 75,000 joules/in. for each arc was utilized. This high deposition SAW technique is currently being used by many shipyards. Due to the close

proximity of the three arcs, it is probable that the total heat input is somewhat additive, however, since there is lack of complete agreement on how to calculate the total heat input, the highest calculated single arc heat input is reported.

The MA and SAW processes have also been widely used in special notch tough material for ING-inner hull, lower temperature applications. However, some limitations on heat input particularly for the SAW process have been imposed in order to obtain the required Charpy impact HAZ values.

Toughness Tests

Small and large scale toughness tests were conducted on both Grade CS and EH36. An attempt was made to relate the results of the larger scale explosion bulge tests to the smaller scale CVN, DT and DWT tests which are more practical for general shipyard procedure evaluation.

Charpy V-notch (CVN)

This test is the most widely used and most economical toughness test and forms the basis for ABS base material and weld metal requirements. The practice of evaluating and testing the HAZ by CVN, though questioned by some researchers, is nonetheless the, toughness test usually specified by most designers and regulatory bodies. ABS requires such testing when EG and ES welding procedures are used for special applications where retention of notch toughness is a primary consideration. CVN test temperatures and' results for the MMA and SAW welds in ABS Grades CS and EH36 are given in Table 1.

Dynamic Tear (DT)

This test was selected because researchers[2,3] have claimed that the DT results are more representative of service than the CVN test. In this investigation a 5/8 in. thick specimen was used, since this size specimen

is a proposed standard, and testing can be carried out in a shipyard using modified DWT machine equipment. DT test temperature and results for the MMA and SAW welds in ABS Grades CS and EH36 are shown in Figures 4 and 5 respectively.

NDT Drop Weight Test (DWT)

This test defines the nil ductility temperature (NDT). DWT is often utilized as an alternate to the CVN test and the necessary equipment is available in many shipyards. The method of conducting this test is described in ASTM A208.[4] The DWT-NDT temperatures for the MMA and SAW welds in ABS Grades CS and EH36 are shown in Figures 4 and 5 respectively.

Explosion Bulge Test

Explosion bulge tests were conducted to evaluate the combined joint toughness and are considered appropriate for this investigation because of the extensive background information available on this test, and its correlation with service temperature.[5] [6] Explosion bulge tests were conducted using standard procedures and are indicated in Reference (l). Appropriate explosion bulge test temperatures for CS and EH36 weldments were selected on the basis of CVN and DT tests. The temperatures selected were approximately 50F above the NDT temperature for each material.

The test temperatures were as follows:

		Explosion Bulge Temp.
Grade CS	-70	- 2 0
Grade EH36	-90	-40

Each spechn was subjected to three shots or separation, whichever occurred first. After each shot the specimens were examined, location of cracks . noted,and thickness reduction and bulge height measured. The results of tests for the MMA and SAN welds in ABS Grades CS and EH36 are shown in Tables 2 and 3 respectively.

Other Tests

The weldments *were* nondestructively tested by radiography and ultrasonic inspection to ABS requirement for hull welds, and transverse tensile, all weld metal tensile, side bend and hardness tests were carried out on specimens representative of each grade and welding process[1]. These,test results are reported in Reference (l).

ANALYSIS OF RESULTS

Small Scale Toughness Tests

The notch location with respect to the small scale toughness tests for both MMA and sAW are A- in Figures 1, 2 and 3. As indicated therein the proportion of weld, HAZ and unaffected base material in each test varies. This variation can be assmd to account for much of the scatter and poor correlation of the small scale test results.

Grade CS Weldments - The small scale toughness test results in the HAZ are summarized as follows:

		Base	MMA	SAW
CVN @	-4F	100	87	68
	-50F	45	23	68
DT @	70F	935	1082	860
	20F	920	177	525
	- 4F	1000	125	558
DWT		-70F	-20F	-40F

The lowest average CVN values in the HAZ are indicated.

The MMA CVN tests at -50F and the DT tests at -4F indicated marked degradation from the base metal properties, and the SAW CVN and DT tests indicated none or considerably less degradation for the SAW. In addition, the DWT-NDT temperature for SAW is 20F lower-than that for MMA. A conclusion based on a review of all of this data would indicate better HAZ toughness properties of the SAW than the MMA. Better overall performance in a composite weldment test such as the explosion bulge test could be predicted.

Grade EH36 Weldments - The small scale toughness test results in the HAZ are summarized as follows:

		Base	MMA	SAW
CVN @	-40F	62	37	41
	-70F	38	17	--
DT @	70F	865	61.5	847
		985	200	--
	-40F	108	87	105
DWT		-90F	-80F	-70F

The CVN tests at -40F for both the MMA and"SAW indicated similar degradation from base metal properties. The DT tests at -40F and the DWT-NDT temperature for both the, MMA and SAW indicated little degradation from base metal properties. A conclusion-based on a review of all this data would indicate similar HAZ toughness properties for the MMA and SAW. Similar overall performance in a composite weldment test such as the explosion bulge test could be predicted.

<u>ExpIosion Bulge Test</u>

Grade CS Weldments - The SAW weldments tested at minus 40F fractured through the base material into three pieces on the first shot with little reduction in area. The subsequent explosion bulge tests on the CS weldments were conducted at -20F . The remaining SAW and one of the two MMA weldments exhibited approximately 11% reduction when exposed to three shots with no visible cracks. The other MMA weldment fractured on the third shot through the base material. For reference see Table 2 and Figures 6 and 7.

The SAW weldment did not clearly exhibit better explosion bulge performance than the MMA *as the* small scale HAZ toughness tests would tend to indicate

The above results indicate that MMA and SAW weldments in CS material, with the welds axis perpendicular to the primary direction of rolling, can be expected to perform satisfactorily at -20F under dynamic service conditions

similar *to* those experienced during explosion bulge testing. No preferential HAZ cracking was observed. This analysis is considered conservative as the loading conditions experienced in LFG and ING ship hulls is not believed to be nearly as severe as that experienced during bulge testing.

Grade EH36 Weldments - One of the two MMA and both SAW weldments "tested at -40F exhibited 7 to 10% reduction with no visible cracks after 3 shots. The remaining MMA weldment fractured principally through the base plate on the second shot without preferential cracking in the HAZ. For reference see Table 3 and Figures 8 and 9.

The above results indicate that SAW and MMA weldments in EH36 material, with the weld axis perpendicular to the primary direction of rolling can be expected to perform satisfactorily at -40F under dynamic service conditions similar to those experienced during explosion bulge testing. No preferential HAZ cracking was observed.

DISCUSSIONS

Test Temperature

In considering the significance of the test results it should be recongized that the loading rate and the extent of deformation involved in explosion bulge testing *are* far greater than those encountered by hull materials under the usual service conditions. Accordingly brittle performance in the explosion bulge test at a particular test temperature should not be considered to imply brittle perfomnce at the same temperature under the lower loading rates of *service* conditions in a merchant ship structure. However, ductile performance in the explosion bulge test would imply ductile performance of a crack free weld at service conditions ,at the same temperature. In this connection satisfactory performance could be expected under dynamic loading conditions for CS down to -20F and for EH36 down to -40F.

Orientation of Welds

The weldments used in this program were fabricated as part of the research program reporbed in Reference (l), with the welds axis perpendicular to the direction of roll in order to simulate erection butts in the side shell and deck of a ship; and the HAZ toughness tests from these weldments evaluated the longitudinal direction with respect to the plate rolling. However, as previously discussed most of the procedure-and production tests for welding procedures used in low temperature applications are conducted with the toughness test evaluating the transverse plate direction.

Since the transverse toughness of the base material can be controlled by selective steel making *practices* it is-quite probable that similar results could be expected from weldments prepared with the weld axis longitudinal to the primary rolling direction if similar base material properties are furnished. However, in order to insure correlation of the results some additional large scale *tests* should be conducted on weldments prepared longitudinal to the primary rolling direction.

CONCLUSION

On the basis of this investigation and the results obtained, the following conclusions have been made:

1. In the case of the ABS Grade CS material, the explosion bulge results indicated that MMA and SAW wehlments in this grade, with the weld axis perpendicular to the primary direction of rolling, can be expected to perform satisfactorily at -20F under the service conditions experienced in LPG and LNG ship hulls.
2. In the case.of the ABS Grade EH36 material, the explosion bulge results indicated that MMA and SAW weldments in this grade, with the weld *axis* perpendicular to the primary direction of rolling, can be expected to perform satisfactorily at -40F under the service conditions experienced in LPG and LNG ship hulls.

3. Similar results to those in this study could be expected from weldments prepared with the weld axis longitudinal to the primary rolling direction if material with *transverse* properties similar to the longitudinal properties utilized in this study *are* employed.

REFERENCES

1. "Toughness Evaluation of Electrogas and Electroslag Weldments," Project Report by Bethlehem Steel Corporation in cooperation with U.S. Maritime Administration, March 1975.
2. Pellini, W. S. - "Principles of Fracture-Safe Design," Part II, Welding Journal, Vol. 50, No. 4, Research Suppl. 147-s, April 1971.
3. Rolfe, S. T., Rhea, D. M. and Kugmanovic, B. O. - "Fracture Control Guidelines for Welded Steel Ship Hulls," Ship Structure Committee, Ser. No. SSC-24-4, 1974.
4. Annual Book of ASTM Standards, Part 31, Designation; E208-69: American Society for Testing and Material, pp. 597-616.
5. Pellini, W. S. and Puzak, P. P. - "Fracture Analysis Diagram Procedures for the Fracture-Safe Engineering Design on Steel Structures," NRL Report No. 5920, U.S. Naval Research Laboratory, 1963.
6. Hartbower, C. E. and Pellini, W. S. - "Investigation of Factors which Determine the Perforn=nce of Weldings," Welding Research Supplement, Oct. 1951 p. 504-s.

TABLE 1

CHARPY IMPACT TEST RESULTS [1,2]

ABS Grade CS

Welding Method CVN Tested at - 4F	MMA	SAW
Weld	46.6	58.0
Fusion Line	81.5	90.0
lmm	87.1	69.0
3mm	94.8	89.0
5mm	117.0	74.0
7mm	96.5	71.0
9mm	96.6	68.0
Base Metal	110.0	110.0
CVN Tested at - 50F		
Weld	6.6	23.0
Fusion Line	43.0	---
lmm	23.0	68.0
7mm		75.0

ABS Grade EH36

Welding Method GVN Tested at - 40F	MMA	SAW
Weld	42.6	38.0
Fusion Line	52.6	41.0
lmm	47.8	52.0
3mm	51.9	46.0
5mm	39.6	51.0
7mm	37.0	42.0
9mn	59.9	49.0
Base Metal	62.0	62.0
CVN Tested at -70F		
Weld	27.0	
Fusion Line	17.0	
5mm	40.0	
7mm	37.0	

(1) Average of 3 or more tests

(2) This table includes results previously reported for comparative purposes.

TABLE 2

ABS GRADE CS EXPLOSION BULGE TEST RESULTS (1)

Specimen No.	Welding Method	Test Temp., F	Shot No.	% Thickness Reduction A	B	Depth of Bulge(in.)	B	Remarks
C-1	MMA	20	1		3.2		1.5	NO visible cracks.
			2	8.6		2.6	2.6	No visible cracks.
			3	13.5	13.4	3.3	3.4	NO visible cracks.
C-2	MMA	20	1	2.5	2.4	1.3	1.3	No visible cracks.
			2	7.3		2.5	2.5	No visible cracks.
			3	12.1	10:9	3.3	3.3	No visible cracks.
C-3	EG	20	1	2.3	2.3	1.4	1.4	No visible cracks.
			2	5.8	6.1	2.7	-	Plate separated along Weld with crack radiating from center area into base material 6.5 in. long.
C-3A	EG	20	1	4.2			1.7	No visible cracks.
			2	9.4	8.8	2.8	2.8	No visible cracks.
			3			-	-	Longest Crack 13.2 in. Large piece broke out B side at center and a large piece almost broke out of .A side at center. Separation along weld almost to edge on both sides. Cracks into base material from center area 4.5 in. & 1.5 in. long.
C-4	EG	20	1	2.6			1.5	No visible cracks.
			2	6.2	6.7	2.6	2.6	Ho visible cracks.
			3	9.4	12.2		3.5	Plate separated along weld with 2 cracks radiating from center area into base material 4.5 in. & 5.4 in. long.
C-5	SAW	20	1		3.0	1.6	1.5	No visible cracks.
			2	8.5	7.6	2.6	2.6	No visible cracks.
			3	13.6	12.6	3.4	3.4	No visible cracks.
C-6	SAW	20	1	2.7	2.5	1.2	1.2	No visible cracks.
			2			2.4	2.4	No visible cracks.
			3	10.8	12.4	3.4	3.5	Longest Crack 17.8 in. Crack in base metal across weld.
C-7	ES	20	1		3.2	1.4	1.5	No visible cracks.
			2	7.4			2.5	No visible cracks.
			3	12.3	12.7	3.3	3.3	No visible cracks.
C-8	ES	20	1	3.0	3.5		1.4	No visible cracks.
			2			2.6	2.5	No visible cracks.
			3	11.6	12.6	3.2	3.2	No visible cracks.
CIA	IMA	-20	1	4.0	4.3	1.5		No visible cracks.
			2	8.1	5.4	2.5	2.6	No visible cracks.
			3	-	-			Blew out 3 piece base plate.
C2A	MMA	-20	1	4.0	5.6	1.4		No visible cracks.
			2				2.4	No visible cracks.
			3	12.3	11.4	3.1	3.0	No visible cracks.
C4A	EG	-20	1	1.8	2.5	1.8	1.9	Plate separated - HAZ break.
C5A	SAW	-40	1					Blew out center - base plate failed, 3 pieces.
C6A	SAW	-20	1	2.5	2.4	1.1	1.1	No visible cracks.
			2		7.7	2.2	2.2	Ho visible cracks.
			3	10.1	10.8	2.9	2.9	No visible cracks.
C7A	ES	-20	1	5.6	5.7	1.4	1.4	No visible cracks.
			2	-	-	-	-	Blew out center base metal.
C8A	ES	-20	1	3.6	4.1	1.4	1.4	No visible cracks.
			2	-	-	-	-	Plate separated. Center blew out & crack 7" or 8" along HAZ.

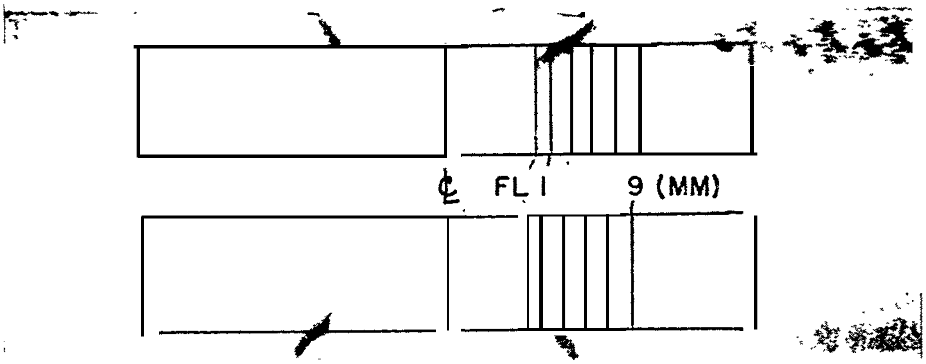
(1) For comparative purposes, this table includes results previously reported.

TABLE 3

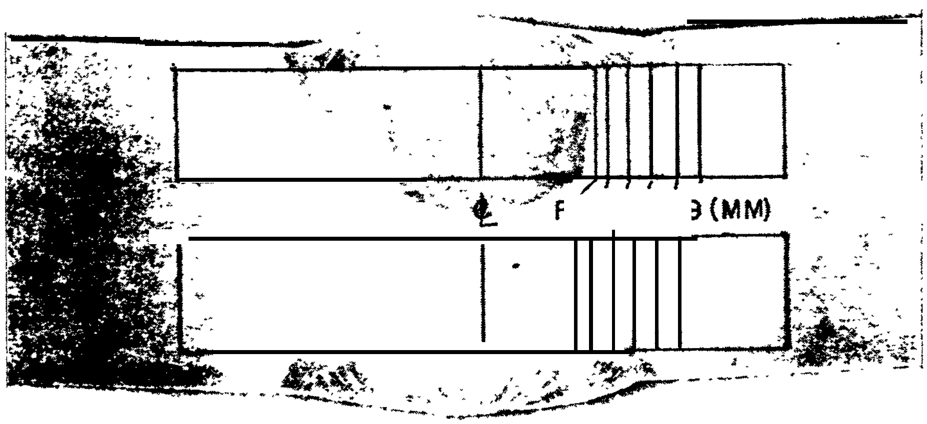
ABS GRADE EH36 EXPLOSION BULGE TEST RESULTS (1)

Specimen No.	Welding Method	Test Temp., F	Shot No.	% Thickness Reduction		Depth of Bulge(in.)		Remarks
				A	B	A	B	
E-1	MMA	0		3.5	3.9	1.4	1.4	No visible cracks.
			1	6.6	7.4	2.3	2.4	No visible cracks.
			3	-	-			Entire center area blew out.
E-2	MMA	0		2.9	3.0	1.3	1.3	No visible cracks.
			1			2.4	2.3	No visible cracks.
			3	10.3	10.4	3.0	3.0	No visible cracks.
E-3	EG	0	1	0.78	0.63	1.8	1.7	Plate separated along weld on B side to near center across weld and along A side of weld to edge. Section of weld broke out of plate. Crack into base material from weld 2 in. long.
E-3A	EG	0	1	2.6	2.2	2.3	1.8	Plate separated along weld. Crack into base material from center area 3.2 in. long.
E-4	EG	0	1	3.5	3.0			No visible cracks.
			2	6.5	6.7	2.3	2.3	No visible cracks.
			3	9.3	9.1	2.9	2.9	No visible cracks.
E-5	SAW	0		3.1	3.0		1.3	No visible cracks.
			1	6.8	6.7	2.3	2.2	No visible cracks.
			3	10.1	10.2	3.0	3.0	No visible cracks.
E-6	SAW	0	1	2.8	3.1			No visible cracks.
			2	6.3	6.8	2.2	2.2	No visible cracks.
			3	10.1	10.2	3.0	3.0	No visible cracks.
E-7	ES	0	1	3.2	3.6	1.3		No visible cracks.
				6.4		2.3	2.3	No visible cracks.
			3		10.2			Longest Crack 5.5 in. Large piece broke out of center area. Separation along weld A side right of center from hole to 1.8 in. of left edge along the weld part of this distance. 5 cracks radiating from center area into base material with longest 5.5 in.
E-7A	ES	0	1	3.3	3.6	1.4	1.3	Longest Crack 10 in. Plate separated along weld from right of center of left edge. Crack across the weld into base material 8 in. long. 3 other Cracks from Center area into base material 3.2 to 3.5 in. long.
E-8	ES	0	1	2.9	2.7	1.5	1.5	Plate separated along weld with 2 small 1 cracks into base material from weld.
E-8A	ES	0	1	1.4	1.1	2.0	1.7	Plate separated along weld.
E-1A	M A	-40	1	3.4	3.8	1.3	1.3	No visible cracks.
			2	-	-			Blew out center - base plate failed.
E-2A	M A	-40	1	3.2	2.9		1.2	No visible cracks.
			2	6.9		2.2	2.2	No visible cracks.
			3	9.5	10.6	2.9	2.9	No visible cracks.
E-5A	SAW	-40	1		3.3		1.1	No visible cracks.
			2	7.5	6.5	2.2	2.1	No visible cracks.
			3	9.5	9.0	3.1	2.8	No visible cracks.
E-6A	SAW	-40	1	2.6	2.8	1.0	0.9	No visible cracks.
			2	4.5	4.8	1.9	1.8	No visible cracks.
			3	7.2	7.1	2.7	2.6	No visible cracks.

(1) For comparative purposes, this table includes results previously reported.

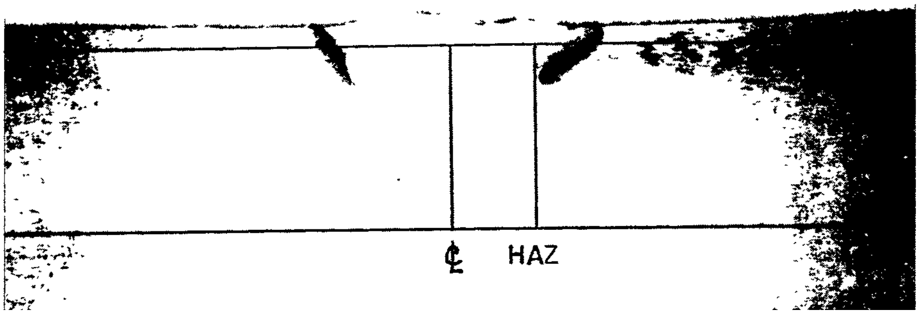


MMA

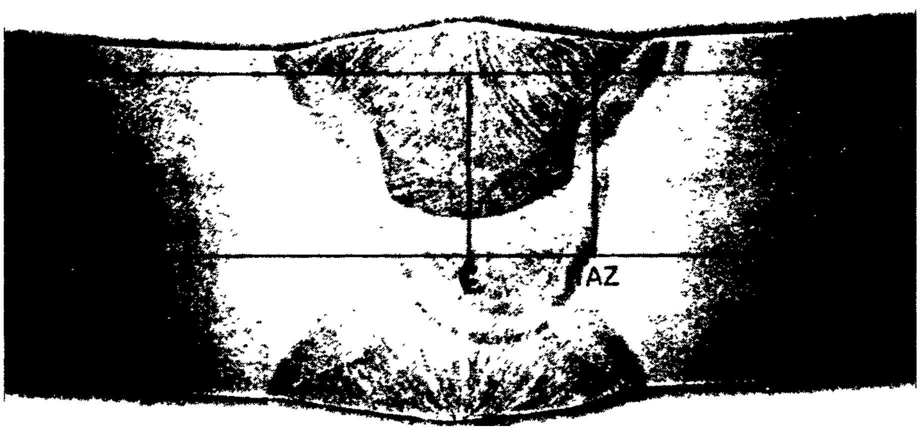


SAW

FIGURE 1 - CHARPY V-NOTCH TEST - NOTCH LOCATIONS

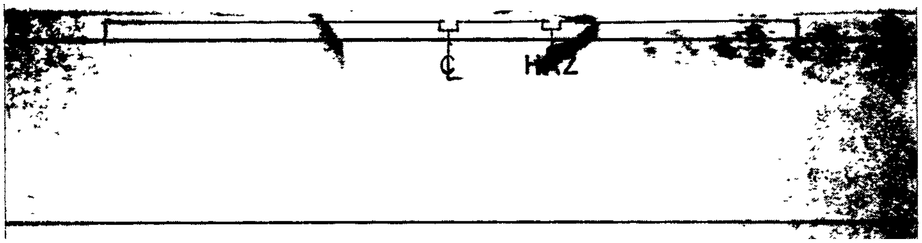


MMA

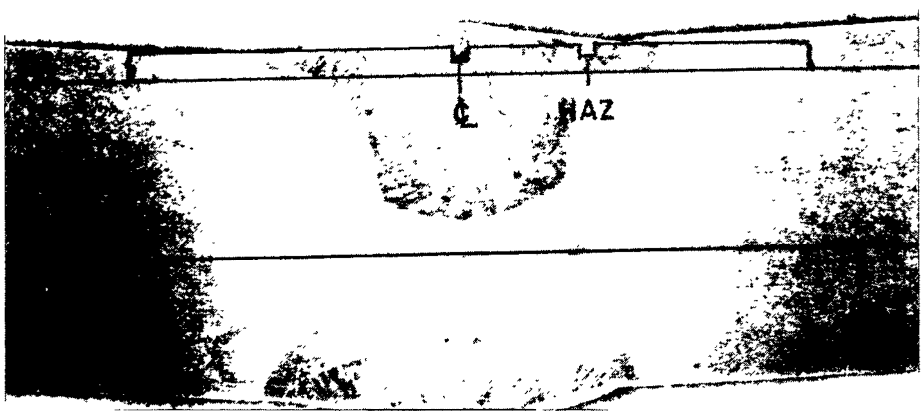


SAW

FIGURE 2 - DYNAMIC TEAR TEST - NOTCH LOCATIONS



MMA



SAW

FIGURE 3 - DROP WEIGHT TEST - NOTCH LOCATIONS

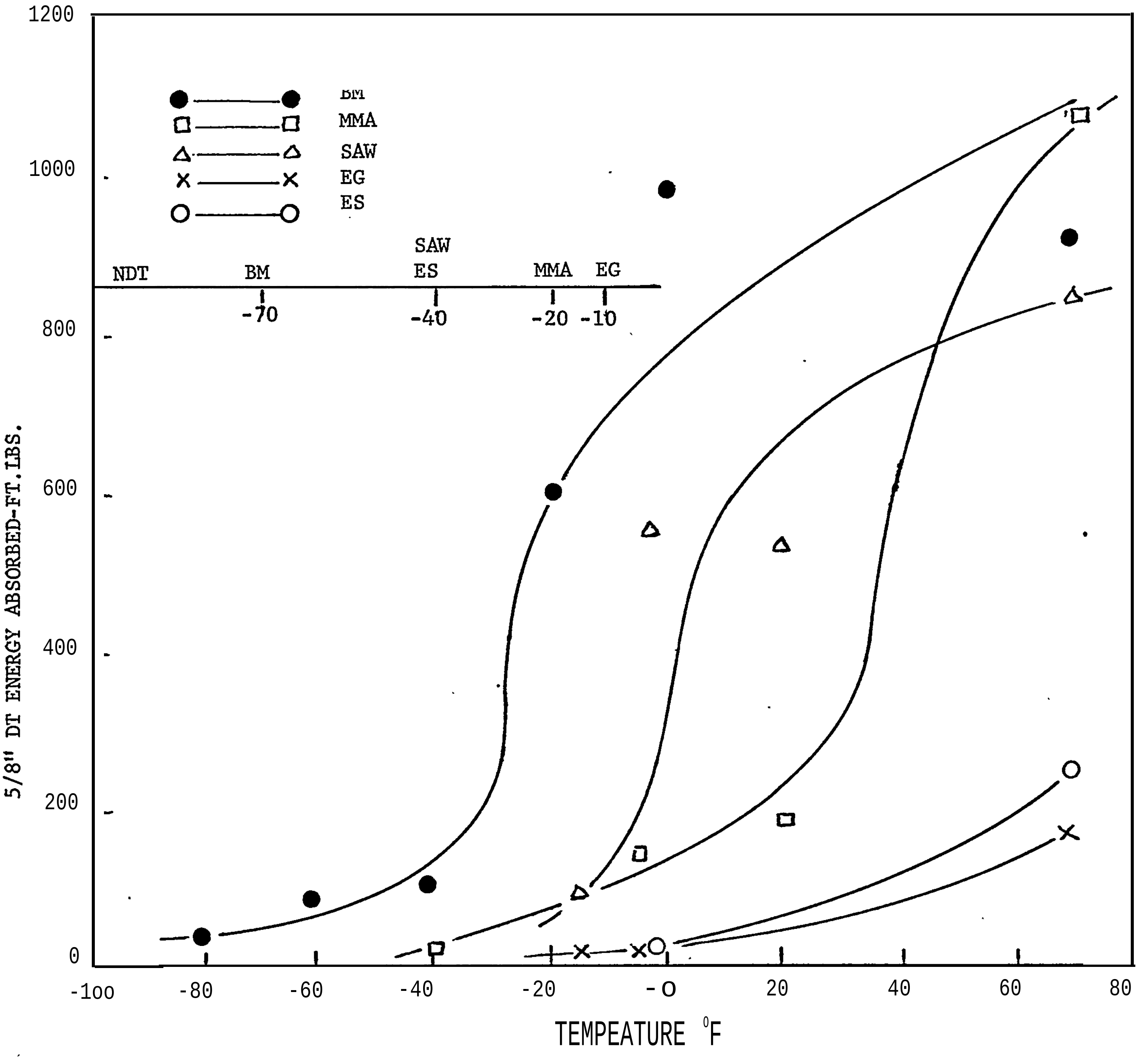


FIGURE 4 - DYNAMIC TEAR AND DROP WEIGHT NDT HAZ TEST RESULTS

GRADE CS MATERIAL

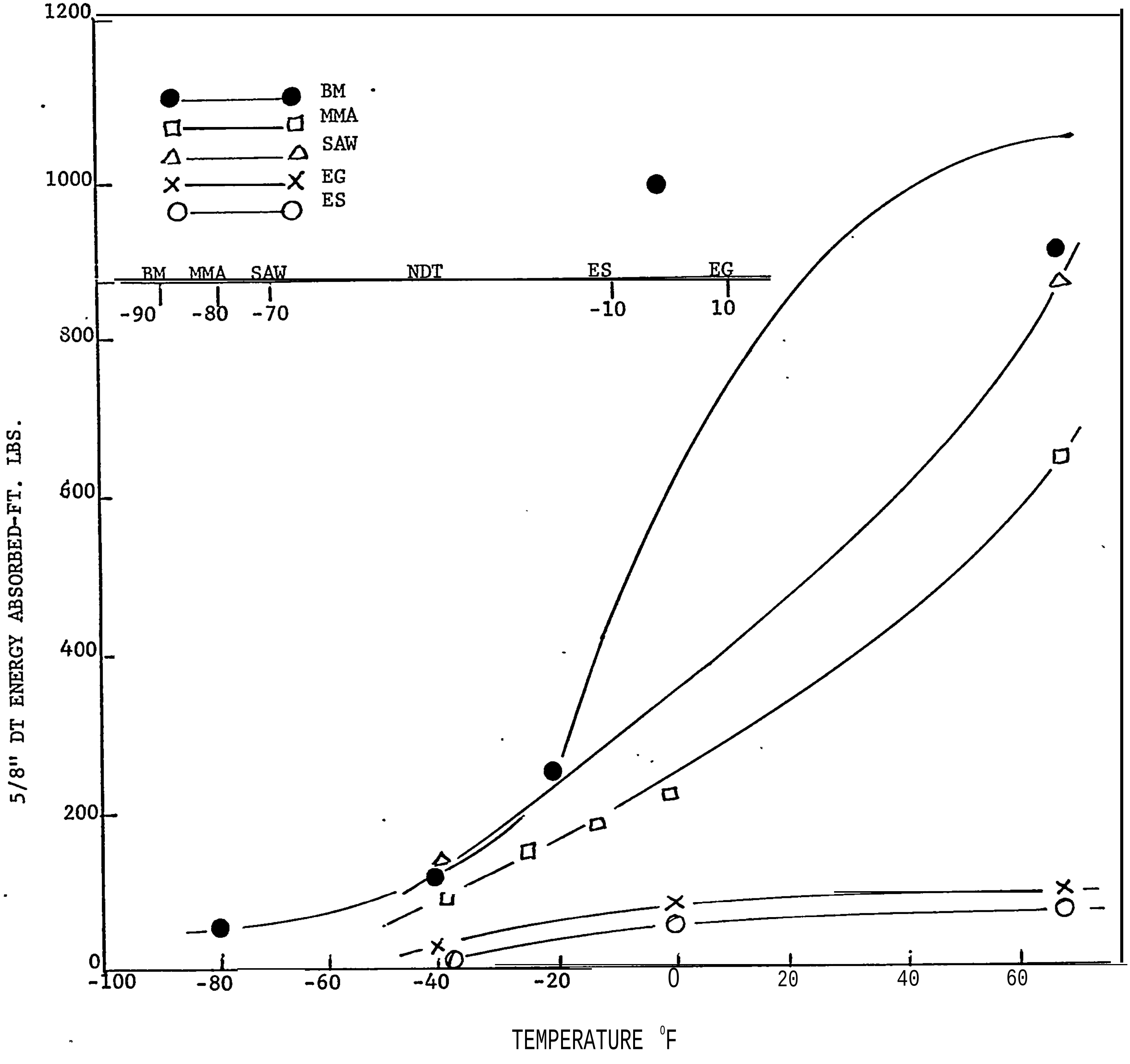
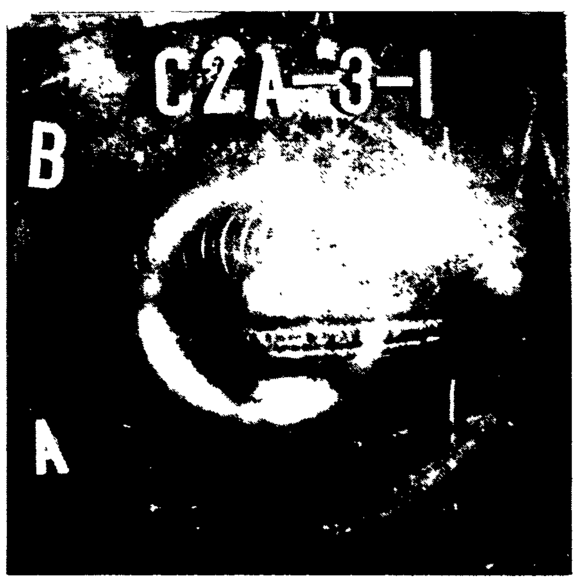


FIGURE 5 - DYNAMIC TEAR AND DROP WEIGHT NDT HAZ TEST RESULTS

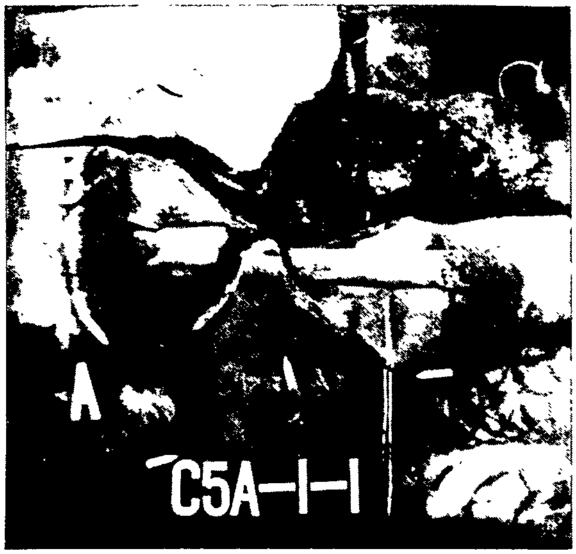
GRADE EH36 MATERIAL

NO. CIA AFTER 3 SHOTS
(TEST TEMPERATURE -20F)

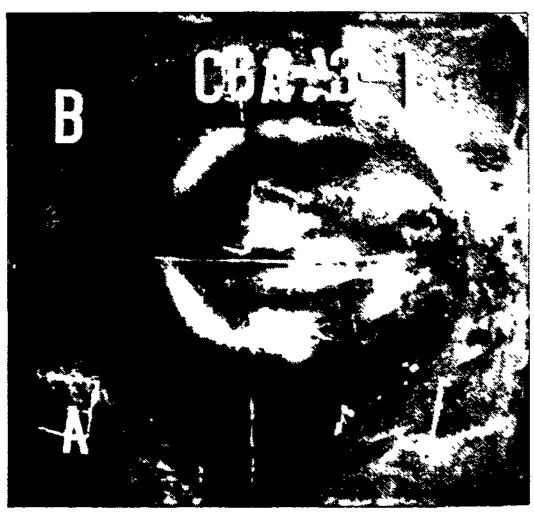


No.2A AFTER 3 SHOTS
(*Test* TEMPERATURE -20F)

FIGURE 6 - MMA GMDE CS EXPLOSION BULGE SPECIMENS



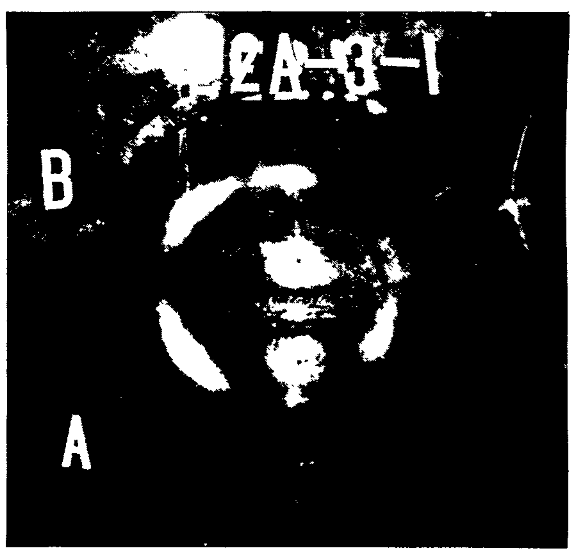
NO.C5A AFTER 1 SHOT
(TEST TEMPERATURE -40F)



NO.C6A AFTER 3 SHOTS
(TEST TEMPERATURE -20F)

FIGURE 7 - SAW GRADE CS EXPLOSION BULGE SPECIMENS

NO. E1A AFTER 2 SHOTS
(TEST TEMPERTURE -40F)



NO. E2A AFTER 3 SHOTS
(TEST TEMPERATURE -40F)

FIGURE 8 - MMA GRADE EH36 EXPLOSION BULGE SPECIMENS

NO. E5A AFTER 3 SHOTS
(TEST TEMPERATURE -40F)

NO. E6A AFTER 3 SHOTS
(TEST TEMPERATURE -40F)

FIGURE 9 - SAW GRADE Eg36 EXPLOSION BULGE SPECIMENS